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Advances in Soil Water Content Sensing: The Continuing Maturation of Technology and Theory

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ABSTRACT

In what has become almost a tradition for *Vadose Zone Journal*, this special section, Soil Water Sensing, follows two related special sections: Advances in Measurement and Monitoring Methods (Vol. 2, Issue 4, 2003) and Hydrogeophysics, which also focused on measurement methods (Vol. 3, Issue 4, 2004). The tremendous interest in vadose zone monitoring reflects the intense societal interest in understanding our environment, the increasing comprehension of scale-dependence of vadose zone properties and processes, and the rapid changes occurring in sensing methods. In this article, we present an overview of the papers, many of which detail methods that rely on soil electromagnetic (EM) responses, including time domain reflectometry (TDR), ground penetrating radar (GPR), and capacitance methods. The papers also indicate key aspects of sensor performance requiring improvement through further sensor development.

Since the work of Topp et al. (1980), which established a theoretical and practical basis for soil water content determination by TDR, and the work of Dean et al. (1987) and Bell et al. (1987) on a resonant capacitance technique for soil water determination, there has been a plethora of related sensors and sensing systems introduced commercially. These sensors respond to EM properties of soil and may be termed jointly *EM sensors*. However, they differ widely in several important characteristics, including susceptibility to interferences, precision, accuracy, and volume sensed.

Many excellent review papers have been written on EM sensors including those given in a recent special issue of the *Vadose Zone Journal*: Advances in Measurement and Monitoring Methods (Vol. 2, Issue 4, 2003). The papers by Robinson et al. (2003), Huisman et al. (2003), and Serbin and Or (2003) presented current methods and issues in TDR, GPR, and horn antenna radar, respectively. In addition to review papers, several chapters in soil methods books have recently been devoted to EM sensors (Ferré and Topp, 2002; Davis and Annan, 2002; Starr and Paltineanu, 2002; Gardner et al., 2000).

Most of the papers presented here attempt to define the characteristics of EM soil water content sensors, calibrate them in various soils and in response to various interfering factors, and evaluate sensors in terms of their ability to respond to changes in the soil bulk dielectric permittivity. A few papers explore other soil properties that are relevant to water content or potential determination. We thank the authors for responding so thoroughly to the call for papers. The resulting group of papers well advances the maturation of technology and theory of soil water content sensing.

The TDR calibration of Topp et al. (1980) for four mineral soils has proven to be accurate to ± 0.02 m^3 m^{-3} for many soils, but does not account for temperature dependency of TDR determined water contents in some soils and is less accurate in many soils containing high ion-exchange-capacity clays (Ferré and Topp, 2002; Topp et al., 2000). In formulating their calibration model, Topp et al. (1980) examined the theory of EM wave propagation along transmission lines and assumed that (for their soils) $\varepsilon'' <<< \varepsilon'$, where ε'' and ε' are, respectively, the imaginary and real parts of the complex electrical permittivity, $\varepsilon = \varepsilon' + \varepsilon''$. For the soils studied by Topp et al. and many others, this is evidently true. This assumption is equivalent to stating that effects of relaxation, soil bulk electrical conductivity (EC), and effective frequency of the TDR pulse, which all affect ε'', are practically negligible (Ferré and Topp, 2002; Robinson et al., 2003). With this assumption, only the real part of the permittivity changes with soil water content; that is, $\theta_v = f(\varepsilon'_a)$, where ε'_a is an apparent permittivity, assumed to be real and determined from the pulse two-way travel time, t_t, along probe rods of length L.

The famous calibration of Topp et al. (1980) relating water content to a polynomial function of ε'_a, and the relationship defining ε'_a in terms of travel time $\{\varepsilon'_a = [c_o t_t/(2L)]^2\}$ have become embedded in the literature of water content sensing by EM sensors, with unintended consequences. It is now common to believe that EM sensors measure ε'_a, whether they work effectively in the time domain (TDR) or the frequency domain (e.g., capacitance sensors). This misapprehension has impeded the understanding of EM soil water sensors in many studies, and has probably impeded the improvement of these sensors as a class.

Topp et al. (1980) also assumed that ε' was independent of measurement frequency, at least at the frequencies ($\approx$1 GHz) commonly associated with the TDR method. This has been confirmed for many soils (Topp and Ferré, 2002). However, many EM sensors operate at frequencies well below the range in which ε' measurement is insensitive to frequency. Also, in TDR systems with long cable lengths or when working in soils containing

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Abbreviations: EC, electrical conductivity; EM, electromagnetic; GPR, ground penetrating radar; HSV, hue, saturation, value; NR-C, nonrelaxing and conductive; NR-NC, nonrelaxing and nonconductive; PITT, partitioning interwell tracer test; REV, representative elemental volume; RGB, red, green, blue; R-NC, relaxing and nonconductive; TDR, time domain reflectometry.

important amounts of clays with large ion exchange capacities that increase the rise time of the TDR pulse (lower its effective frequency), the operating frequency may fall below the insensitive range (i.e., <500 MHz, Kelleners et al., 2005) (Evett et al., 2005). It has been established that the value of ε' increases with decreasing measurement frequency below this range for several clays (e.g., Campbell, 1990; Logsdon and Laird, 2002; Robinson et al., 2005).

There is now abundant evidence that EM methods, even broadband high frequency methods such as TDR, are substantially affected by ε'' in some soils (e.g., soils with large ion exchange capacity) and measurement situations (e.g., long cables that act as low pass filters in TDR systems). That is to say that the measured property, be it a travel time or frequency change, is responsive to both ε' and ε'' (Topp et al., 2000). And, because ε'' includes the quantity $\sigma/(\pi f \varepsilon_o)$ as well as a term due to relaxation effects, ε''_{rel} (more important in low frequency systems), the measured properties are responsive to changes in the conductivity, σ, of the porous medium and to the effective frequency, f, of the measurement system. Because the bulk EC, σ_b, of soils is dependent on soil temperature, T, the measured properties become more or less temperature sensitive as well, depending on the value of σ_b. Because σ_b increases with soil water content, dealing with temperature effects can be daunting. Much of the work reported here attempts to find ways to deal with these responses, understand how soil and sensing system properties affect the responses, and evaluate or calibrate EM sensors in ways that take into account the responses to T, f, ε''_{rel}, and $\sigma_b(\theta_v)$.

It is axiomatic that only direct methods (soil coring or sampling, with gravimetric analysis) can measure soil water content. The indirect methods, whether they rely on neutron thermalization, soil electromagnetic properties, soil thermal properties, or soil color, can at best be identified as soil water sensing methods. Indirect methods measure surrogate properties that vary in some way with soil water content. None measure soil water content directly. For example, the neutron moisture meter counts thermalized neutrons that pass through a detector. The calibration has almost always been considered empirical, largely because theoretical calibrations have not been useful. The EM methods measure travel times (TDR) or frequencies (capacitance). While these measurements are sometimes converted to values of permittivity on the basis of theoretical considerations, usually the Topp et al. analysis, none of the EM sensors measure permittivity directly. In this special issue, we have made an effort to emphasize what is really measured by EM sensors, to frame the discussion in terms of soil water sensing and estimation rather than soil water measurement (except where direct measurements were made), to write of the apparent complex permittivity, ε_a, to emphasize that this is estimated from frequency or travel time measurements and is a function of ε' and ε'' that depends on the particular instrumentation used, and to use the term *dielectric permittivity* rather than dielectric constant to emphasize that ε_a is a variable property. This effort toward using precise language, while not always successful, is essential to reconciling measurement with theory in efforts to advance soil water science and related fields.

OVERVIEW OF SPECIAL SECTION

Robinson et al. (2005) develop, from electrical theory, an analytical model of a series resonance, frequency shift capacitance probe that shows how σ_b affects the probe capacitance even though the imaginary part of the impedance is zero at resonant frequency. In sandy soils with low σ_b at all water contents, the capacitance probe worked well. However, in finer grained soils with σ_b ranging from 0.4 to 2.7 dS m^{-1} at saturation, the theoretical correction for σ_b only partially corrected estimates of the real permittivity as compared with measurements taken with a network analyzer. Estimates of real permittivity from a TDR system connected to the same probe rods were much closer to those from the network analyzer and to estimates based on mass balance water contents and inversion of the Topp et al. (1980) equation. Results suggested that the circuit model could not predict real permittivity accurately due to frequency response damping at the larger EC values, further suggesting that "reliable, accurate water content determination using this type of capacitance probe will be limited to soils with low EC and low dielectric relaxation." Increases in TDR estimates of real permittivity at water contents >0.3 m^3 m^{-3} in one soil may have been due to increased bulk density in packed samples. The authors postulate a mechanism that increases polarization as bulk density and water content increase. They suggest that this may affect the real permittivity at larger water contents in soils with large ion exchange capacity, and they call for further work to elucidate this mechanism.

Recognizing that capacitance sensors may be affected by soil temperature and texture, Polyakov et al. (2005) conducted calibrations of a capacitance probe (model EasyAg 50, Sentek, Australia) in silica sand in the laboratory and in a kaolinitic silty clay loam with moderate shrink–swell potential in the field and laboratory.[1] Calibration equations under controlled laboratory conditions in the sand and in the field soil differed substantially from the manufacturer's calibration, which underestimated water content on the wet end for both media. Studies of the temperature dependency resulted in a value of 0.0012 m^3 m^{-3} °C^{-1} for the field soil at θ_v = 0.29 m^3 m^{-3}, and a value of one third of this in the sand, similar to results for other capacitance probes. Calibration accuracy (RMSE of regression) for the field soil under laboratory conditions was 0.039 m^3 m^{-3}; and for two field calibrations accuracies were 0.031 and 0.048 m^3 m^{-3}. Field calibrations were substantially different from laboratory calibrations and took a convex upward shape, rather than the expected concave upward shape in plots of water content vs. the frequency parameter. The authors concluded that site-specific calibration of the probe improved the accuracy of the water content measurement.

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS.

Field soils with large specific surface area often exhibit a temperature dependency of TDR-derived ε_a and water content. Faced with this behavior in a field site, Logsdon (2005) field-calibrated TDR using water contents derived from nearby neutron probe measurements vs. $\varepsilon_a^{0.5}$ and temperature measured with thermocouples. Soils varied by site and depth, resulting in 21 site–depth combinations. Because clay content and specific surface area (up to 125 $m^2\ g^{-1}$) varied with depth, the resulting calibration coefficients were different by depth and location. A laboratory calibration on repacked soil columns was also done. Temperature dependencies ranged from 0.0001 to 0.008 $m^3\ m^{-3}\ °C^{-1}$ for the laboratory calibration and from 0.00006 to 0.0124 $m^3\ m^{-3}\ °C^{-1}$ for the field calibration. Inclusion of temperature reduced the calibration RMSE values for both field and laboratory. Stepwise regression showed that permittivity derived from TDR measurements of travel time increased with soil specific surface area and decreased with sand content for both laboratory and field data, and it increased with cable length in the field study. Inspection of the waveforms led to the conclusion that soils with larger specific surface areas and larger water contents also had larger σ_b, although no values were measured and the soil was not saline.

Working with three soils having smectitic clay contents of 17, 35, and 48%, Evett et al. (2005) obtained individual linear calibrations for conventional TDR in repacked soil columns with RMSE < 0.01 $m^3\ m^{-3}$, but with soil temperature induced noise on the wet end due to σ_b values approaching 2 dS m^{-1}. Recognizing that $\varepsilon_a^{0.5} = c_o t_t/(2L) = (\varepsilon' + \varepsilon'')^{0.5}$ and that temperature-induced noise was probably due to variations in ε'', they recast their calibration equation in terms of

$$\theta_v = a + b[c_o t_t/(2L)] + c[\sigma_b/(2\pi f_{vi}\varepsilon_o)]^{0.5} \qquad [1]$$

where a, b, and c were fitted coefficients, and both σ_b and an effective frequency, f_{vi}, were determined using TDR waveforms. Using Eq. [1], they obtained a common calibration for the three soils with RMSE < 0.01 $m^3\ m^{-3}$ and a temperature sensitivity of <0.0006 $m^3\ m^{-3}\ °C^{-1}$. Their analysis disregarded any influence of ε''_{rel}, but implicitly included T variations in the determination of σ_b and implicitly included cable length effects in the determination of effective frequency. Coaxial cable lengths varied from 6.4 to 10 m.

Alternative instruments have been proposed that employ a fast rise time pulse as in conventional TDR, but that do not capture and interpret a waveform to find the pulse travel time in the probe. One such device (model Trime T3 tube probe, IMKO Micromodultechnik Gmbh, Ettlingen, Germany) works from within a 1-mm-thick polycarbonate access tube and was studied independently by Laurent et al. (2005) in two soils in France and two in Tunisia. Soils ranged from sandy loam with negligible σ_b to silty clay loam with large σ_b. The factory calibration was not accurate in any soil, but soil-specific linear corrections on Trime-reported θ_v values improved RMSE to a range of values from 0.0099 to 0.0702 $m^3\ m^{-3}$. A correction applied to all data resulted in an RMSE of 0.0453 $m^3\ m^{-3}$. This instrument calculates a "pseudo transit time," which the authors related to soil water contents measured either gravimetrically near the access tubes or by neutron probe in the same access tubes. The resulting curve was highly nonlinear, indicating that the instrument does not work as a true TDR device, for which the relationship would be more nearly linear. A laboratory investigation in media of differing permittivity showed that permittivity measured by a TDR instrument (Tektronix, Beaverton, OR or Agilent, Palo Alto, CA) connected to the Trime probe in its access tube was nonlinearly related to permittivity measured using conventional TDR methods and a trifilar probe in the same media. The same data showed that the Trime instrument was less sensitive to permittivity changes at large values of ε'.

Irrigation scheduling is an important application of lower-cost soil water sensors, but relies on obtaining sufficient accuracy to irrigate well before the soil water reaches wilting point and to not irrigate if the soil is too wet. Plauborg et al. (2005) compared the Campbell Scientific model CS616 (Logan, UT) and Streat Instruments Aquaflex (Christchurch, New Zealand) sensors with conventional TDR in drip irrigated potato fields with soils ranging from sand to sandy clay loam. The CS616 probe has two 30-cm-long stainless-steel rods, and the Aquaflex has wires acting as transmission lines in a 3-m-long insulated ribbon cable that is commonly buried in a trench. Both sensors employ a relatively fast rise time electronic pulse generated in the sensor head, but neither captures a waveform for analysis as in conventional TDR. Slopes of linear regression between the CS616 and TDR determined water contents ranged from 0.59 to 0.96 for the range of textures, and the CS616 often estimated water contents well above field capacity. Coefficients of determination ranged from 0.95 to 0.99, indicating that calibration corrections could be used for each soil. However, during fertigation with NH_4NO_3 and $Ca(NO_3)_2$, an increase in soil solution EC to 1.6 dS m^{-1} caused further overestimation of water content by the CS616. The Aquaflex was only studied in the sand, in which it underestimated water content by up to 0.15 $m^3\ m^{-3}$, resulting in most readings being smaller than wilting point and sometimes negative.

The growing number of EM sensors offered for soil water sensing are evaluated independently and compared in the literature using a variety of techniques and standards in both laboratory and field studies. Jones et al. (2005) suggested standards for evaluating the ability of EM soil water sensors to estimate ε'. The evaluations involve the use of fluids and fluid mixtures to obtain media with different known frequency-dependent dielectric permittivities. Media were successfully formulated to provide a relaxing and nonconductive (R-NC) medium, a nonrelaxing and nonconductive (NR-NC) medium, and a nonrelaxing and conductive (NR-C) medium for testing purposes. A relaxing and conductive medium could not be developed. The latter is needed to represent conditions in soils that are the most challenging for EM sensors, including those with appreciable σ_b and ion exchange capacity. The authors assumed that quality water content estimation follows from quality dielectric measurements and correct calibration measurements. Also discussed is a modeling approach that indicated that there was no change in sampled volume with change in permittivity of the sampled medium. This is at odds with results of other studies (Evett et al., 2002) and other modeling approaches (e.g., Galagedara et al., 2005, for GPR; Nussberger et al., 2005).

In a companion study, Blonquist et al. (2005) evaluated the permittivity measurement ability of seven EM sensors in NR-NC, R-NC, NR-C, and temperature variable NR-NC media. The higher frequency broadband systems (e.g., TDR) were influenced more by a medium's conductivity and temperature than by relaxation effects. Permittivity measurement using lower frequency systems (e.g., capacitance and related methods) was more influenced by conductivity than by temperature and dielectric relaxation. Overall, effects of σ_b, T, and ε''_{rel} were much less for higher frequency, broadband sensing systems. Lower frequency systems were limited in the range of permittivity that they could measure, becoming insensitive at values >40. Some systems do not output apparent permittivity values, complicating the application of these testing standards. The authors suggested concentrating more attention on separation of ε'' and ε' in sensing systems because ε' is directly related to water content, but ε'' is an important component of ε_a (what the sensor responds to) for many measurement systems and soil conditions.

Electromagnetic soil water sensors of the same model are often assumed to be uniform. The intersensor variability of the Hydra Probe (Stevens-Vitel, Beaverton, OR) sensor was shown by Seyfried et al. (2005) to be no more than 0.012 $m^3\ m^{-3}$, which becomes a lower limit value for the accuracy obtainable when using a common calibration for a group of these sensors. This sensor outputs voltages, one of which is stated to be a function of ε', and the other a function of ε''. The value of ε'' is related to the loss tangent, which includes $\sigma/(\pi f \varepsilon_o)$ and is of greater importance for lower frequency sensors such as the Hydra Probe (50 MHz). Utilizing estimates of the loss tangent, soil-specific calibrations were developed for 19 soils, giving accuracy approaching that of TDR for most of these. Accuracy was better than that possible using factory-supplied calibrations for the corresponding soil texture classes. The variability of calibration coefficient values using a linear model vs. $(\varepsilon')^{0.5}$ was greater than that expected for TDR, illustrating the influence of measurement frequency, and establishing that a general calibration, such as is useful for many soils with TDR, is not generally possible for lower frequency sensors.

Combining an EM sensor with another sensor has several advantages, including the ability to measure temporal variability of at least two different soil properties with minimal soil disturbance on the same soil volume. Building on work by Ren et al. (2003), Heitman et al. (2003), and Mori et al. (2003), Ren et al. (2005) used a miniature (0.02-m-long rods with 0.006-m spacing) trifilar TDR probe incorporating a heat pulse sensor to evaluate the TDR and heat pulse methods on nearly identical soil volumes of eight soils (sandy loam to clay loam in texture). This "thermo-TDR" probe had a radial sensitivity of approximately 11 mm in the TDR mode and approximately 14 mm in the heat pulse mode, indicating sampling volumes of approximately 7.6 and 12.3 cm^3 for TDR and heat pulse methods, respectively. With careful calibration of the TDR probes and determination of the heat capacity of the solid phase on oven-dried samples, both methods were capable of determining θ_v with fair accuracy. The RMSD between gravimetric values of θ_v and those determined by TDR was 0.018 $m^3\ m^{-3}$ for undisturbed core samples compared with a RMSD value of 0.021 $m^3\ m^{-3}$ for comparison of gravimetric with heat pulse measurements. Values of RMSD for comparisons of θ_v for uniformly repacked samples were nearly identical at 0.23 and 0.22 $m^3\ m^{-3}$ for TDR and heat pulse methods, respectively, indicating that spatial heterogeneities in the undisturbed samples caused greater error in the heat pulse method values of θ_v. Because the estimated sampling volumes are two to three orders of magnitude smaller than the representative elemental volume for water content in many field soils, such small probes are unlikely to become widely used for field measurements. It should be noted that short (0.02 m) TDR rods, such as those used here, result in such small travel times that the resolution limits of the TDR instrument (Tektronix model 1502) and end effects become an important source of noise in the measured travel time (Zegelin et al., 1992). Also, the small diameter (1.3-mm) rods used may approach the size of soil aggregates, causing other problems for TDR waveform interpretation (White et al., 1994). For this reason TDR probe rods are commonly an order of magnitude, or more, longer and have larger diameters than used here, with resulting improvements in precision of travel time and water content determinations.

Other properties that can be important indicators of soil water status include the soil thermal properties, the soil albedo, and soil water suction. Several authors have reported relationships between soil albedo and water content (e.g., Idso and Reginato, 1974; Idso et al., 1975; Post et al., 2000). Extending this work, Persson (2005) investigated the relationship between soil color and surface water content in both the red, green, blue (RGB) and the hue, saturation, and value (HSV) color spaces. A relationship between the values of S and V and the water content was found that was accurate to better than 0.017 $m^3\ m^{-3}$ in two soils and to 0.025 $m^3\ m^{-3}$ in another two soils. The relationship was strongest for light-colored soils with small organic matter contents. Soil surface water content is a key determinant of evaporation rates and light absorption, so this method may become important in studies of surface energy and water balances.

It is difficult to relate soil water suction directly to water content because the relationship is hysteretic. Still, for plant function, the total soil water suction is very relevant. Agus and Schanz (2005) compared the noncontact filter paper method, soil psychrometry, a relative humidity sensor, and a chilled mirror dew point sensor for laboratory determination of total soil water suction. The chilled mirror technique was considered to produce the most accurate results. The relative humidity sensor exhibited systematic error at smaller suctions where the psychrometer was more accurate but slower to respond. Therefore the relative humidity sensor was more suitable for measuring larger suctions. The filter paper method took a very long time (up to months) and so measured the soil water suction after redistribution of water had taken place in the sample.

The EM methods so far described sense relatively small soil volumes. Two methods that sense much larger volumes are GPR and the partitioning interwell tracer test (PITT). An excellent review of the GPR method of estimating soil water content was given by Huisman et al. (2003) in the Advances in Measurement and Monitoring Methods special section of the *Vadose Zone Journal*. They concluded that one of the important research questions that remain is what is the sampling volume and spatial resolution of the GPR methods? Numerical modeling was used by Galagedara et al. (2005) to begin to address this question by examining the relationship between sampling depth and frequency of the direct ground wave GPR method for different water contents. Sampling depth decreased strongly as frequency increased, the relationship between GPR wavelength and sampling depth being strongly linear. At 100 MHz, sampling depth increased from approximately 0.5 m at $\theta_v = 0.35$ m^3 m^{-3} to about 1.1 m at $\theta_v = 0.05$ m^3 m^{-3}. At 900 MHz, sampling depth increased from about 0.1 m at $\theta_v = 0.35$ m^3 m^{-3} to about 0.16 m at $\theta_v = 0.05$ m^3 m^{-3}. However, sampling depth was greater for dry over wet soil layers as opposed to wet over dry layers. Also, as EC increased, the maximum upper dry layer thickness decreased. Estimated water contents plotted vs. the average water content of dry and wet layers used in the model were scattered about the 1-to-1 line.

Water saturation is an important porous medium property that influences pollutant transport. Common soil science tools for measuring water content, like the neutron probe and TDR, measure volumes that are too small to represent the large volumes commonly involved in pollutant transport problems unless many samples are taken. They may also be influenced by the properties of landfill or mine tailings in unknown ways. The PITT has been shown to be useful for estimation of the degree of saturation by NAPLs; and Li and Imhoff (2005) studied its use for estimating saturation of water alone. They found that, for small air–water mass transfer rates, the PITT methods resulted in underestimation of water saturation, and that achieving better results entailed very long sampling times. They also concluded that using multiple tracers with different Henry's Law constants did not lead to identification of mass transfer problems that limit the method.

INDICATIONS FOR FUTURE WORK

In so far as laboratory work can address it, the studies discussed here rather thoroughly encompass the state of the art in EM sensors that are inserted into soil or used in access tubes in the soil. Many of the problems plaguing EM sensors are now well enough understood that new sensors can be designed to overcome them. Chief among these problems are susceptibility to interference from soil $\sigma_b(\theta_v)$ and temperature variations, and thus to content of salts and clay types that enhance $\sigma_b(\theta_v)$. The studies herein and others that involved fieldwork generally indicate that there are problems to be overcome to make many EM sensors truly useful in the field and that soil specific calibration may be necessary to improve the accuracy of EM sensors (McMichael and Lascano, 2003). Variations in field soil σ_b due to variations in θ_v, T, and addition or removal of salts through precipitation, irrigation, drainage, and fertilization still render many EM sensors unreliable.

Also, the work presented here only peripherally discussed the implications of the small measurement volumes of most EM sensors (except GPR), which are typically at least an order of magnitude smaller than that of the neutron moisture meter, and which are smaller than the representative elemental volume (REV) for soil water content in many soils. Because the REV becomes larger in most soils as they dry, this is particularly a problem at smaller water contents (Allen et al., 1993; Dickey et al., 1993; Famiglietti et al., 1999; Hawley et al., 1982; Hupet and Vanclooster, 2002; Schmitz and Sourell, 2000). The implication is that unreasonably large numbers of EM sensors or access tubes may be required to address field variability of soil water content and obtain mean water contents that are representative of plant and hydrological processes at the plot or field scale or larger.

Thus, the challenges to scientists are clear. First, we need to better understand the physics of soil water and electromagnetic wave interactions with clay minerals that have large ion exchange capacities and surface areas, and we need to keep in mind that the increase of ε' with decreasing frequency is soil dependent. Second, the next generation of EM soil water sensors must address interferences due to $\sigma_b(\theta_v)$ and interacting factors such as soil bulk density. They probably should operate at frequencies >500 MHz (Kelleners et al., 2005), and they must sense volumes large enough to encompass the REV in most soils.

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